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Necessity of Including Maintenance Traffic Delay Emissions in Life Cycle Assessment of Pavements

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Abstract

The Life Cycle Assessment (LCA) is a method which aggregates the environmental impacts associated within the life cycle of a pavement. Incorporation of LCA has been mostly focused on the emissions produced in the construction phase and in its constituents, such as material extraction and manufacturing, hauling of materials, etc. Less emphasis has been given to emissions caused by traffic delays during maintenance operations due to lack of well-defined methodology and unfamiliarity about the magnitude of these emissions. In this study, an approach is proposed to include traffic delay emissions by combining Users Cost approach of Life Cycle Cost Analysis (LCCA) with Motor Vehicle Emissions Simulator (MOVES 2014) developed by the United States Environmental Protection Agency (US EPA). The LCA was performed for four different pavement designs and their Global Warming Potential (GWP) were included in the assessment. The GWP of the four designs with and without considering traffic delay emissions (in carbon dioxide equivalents: CO_2e) were 53, 51, 50, and 22 versus 6.1, 4.5, 4.3, and 13 thousand tons per mile, respectively. The differences between the GWP with and without traffic delay emissions suggests that there is a need to include traffic delay emissions in the LCA to better estimate environmental impact.

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Keywords: Life Cycle Assessments, Traffic Delay Emissions, Life Cycle Cost Analysis, Global Warming Potential.

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1. Introduction

Construction of highways requires a significant amount of natural resources, capital, workforce, etc., and pavement design drives these parameters. Pavements have significant potential to influence the environment, and economy. Hence, various alternate pavement designs needs to be developed and evaluated thoroughly from design to end of life. Over the years, practitioners have proposed to utilize the Life Cycle Cost Analysis (LCCA) approach to appraise the costs associated with long-term highway usage, and the environmental impacts using the Life Cycle Assessment (LCA). The LCCA of pavements estimates the various costs in a pavement life cycle and converts the anticipated costs to present worth. LCCA helps to understand the economic efficiencies between various alternative designs. Many state highway agencies have implemented LCCA to analyze alternative designs [1] to select the most economical design. Federal Highway Administration (FHWA) has developed a LCCA software product named RealCost2.5 to facilitate the numerical calculations in accordance with FHWA's best practice methods [2]. The LCA, proposed by International Organization of Standards (ISO), is a tool that comprehensively quantifies environmental impacts throughout the life of a highway. Although the research in LCA is still developing, it has been in use to evaluate pavements for over a decade [3]. The LCA application studies have mainly focused on material extraction, production, transportation, and construction phases while ignoring the impacts caused by traffic delays during scheduled maintenance operations. The decisions that are made based on partial LCA may lead to wrong conclusions and it will be worse if the omitted sections in LCA have larger impacts on the overall environmental footprint of a pavement [4].

2. Literature Review

Impacts of traffic delays on the LCA have been analyzed by researchers over the years. Kendall et al. [5] evaluated two alternate bridge deck designs and estimated that the construction traffic delays emissions caused 79% of the total emissions. Santero and Horvath [6] analyzed eight components of various phases of the LCA namely: 1) material extraction and production, 2) transportation, 3) onsite equipment, 4) traffic delay, 5) concrete carbonation, 6) roadway lighting, 7) albedo, and 8) rolling resistance . They stated that components like traffic delay emissions, lighting, location etc., are all context related factors and the impacts of a given component varies geographically.

Hanson [7] performed a study to determine the relative share of various components of the LCA of pavements including traffic delay emissions for a 50 year life time. The authors explicitly stated that the traffic disruption for this particular case study was minimal due to low traffic volume but, it can be a potential source of emissions for other cases. Similarly, the relative significance of work zone traffic delay emissions with respect to other phases in rural areas was done by Ting et al.[8] and the study concluded that impacts due to work zone traffic were very small as compared to other processes in the LCA of pavements in rural areas.

It is apparent from the above studies that traffic delay emissions is context based, that is highways in rural areas, low traffic volume roads, and maintenance strategies that do not develop queues have a minimal impact on traffic delay emissions [6]. On the other hand, in urban areas and highways with higher AADT, traffic delay emissions are significant and can surmount the other components of the LCA. Omitting emissions due to traffic delays in such cases may significantly undervalue the life cycle emissions [4], [9], [10]. In summary, emissions from traffic delays can be substantial and have been overlooked in LCA of pavements due to the lack of practical tools and needs to be evaluated as more tools for evaluation become available and was focus of this study.

3. Objectives

The following are the objectives formulated for this study:

- Develop a practical methodology for estimating emissions due to traffic delays using the best available tools and methodologies.
- Provide necessary information for decision makers in selecting the best designs and alternative maintenance strategies.

4. Numerical Example

The need of this study is explained through an example. Four equivalent pavement designs were developed in this study. Equivalent design implies that each alternative was designed to perform equally, and provide the same level of service, over the same performance period [11]. The designs were developed based on the recommendations of the Texas Department of Transportation pavement design guide. Each of the design consisted of six-lane highway (three lanes on each side) and has an Annual Average Daily Traffic (AADT) of 61,236 on each side, as per 2014 traffic count. The traffic consists of 10.6% of trucks and 89.4% of passenger cars. The annual growth of traffic is assumed to be 0.75% and pavements were designed for 30 years. The four pavement designs varied in their material composition and thickness of layers. On average, designs 1, 2, and 3 had two rehabilitations during a 30 year period and the design 4 required a minor rehabilitation. For this study, it was assumed that the hauling distances of all raw materials as 50 miles to the plants and 12 miles from the plants to construction sites.

Greenhouse gas emissions were accounted during material extraction and manufacturing, transportation, and construction of various pavement designs. The materials and equipment required for maintenance operations were also included. The use and end of life phases of pavements were not considered. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) by Argonne National Laboratory (U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy) was employed to estimate the emissions from the material extraction and manufacturing phase as well as the transportation phase. Construction equipment emissions are drawn from EPA's NONROAD model [12]. The type of equipment and working hours of equipment were estimated based on the RSMeans data [13] for the El Paso Texas region. The inventory of greenhouse gases are characterized into Global Warming Potential (GWP) by transforming the greenhouse gases into carbon dioxide equivalents. The conversion factors were provided by EPA's impact assessment tool "Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI)". Initially the Global Warming Potential (GWP) of the four designs was evaluated without considering the traffic delay emissions.

5. Proposed Methodology

During maintenance of highways, the vehicles are subjected to different operating conditions like reduced speed, queuing, frequent braking etc., and these changes in vehicle operations cause's additional impacts on environment. These additional impacts can be captured by: 1) characterizing the traffic flows, 2) simulating the traffic, and 3) having a reliable data base for estimating emissions from vehicles under different working conditions. The Motor Vehicle Emission Simulator (MOVES) tool meets these requirements and was used in this study.

5.1. Motor Vehicle Emission Simulator (MOVES 2014)

MOVES is developed by the U.S. Environmental Protection Agency (EPA) that provides an accurate estimate of emissions from highway vehicles to off-road mobile equipment under a wide range of user defined conditions [12]. The MOVES model includes a default database that summarizes emissions and relevant information for the entire United States [12]. The database utilizes the data from many sources, including EPA research studies, Census Bureau vehicle surveys, FHWA travel data, and other federal, state, local, industry and academic sources. Project level analysis was considered in this study as it is most suitable for analyzing alternate designs and, it comprises of two phases. In the first phase of modeling, general information and required inputs are affirmed such as vehicle types, time periods, geographical areas, pollutants, vehicle operating characteristics etc.

In the second phase, the "Project Data Manager" tool enables the user to enter specific data from the project into an input database. User-defined or project-specific details can be entered into input database. The primary inputs required are "Links" and "Link Source Types". A link in MOVES indicates the segment of road that is being modelled. "Links" requires nine inputs such as: Link Id (like inbound or outbound), County Id, Zone Id, Road Type, Link Length, Link Volume, Link Average Speed, Link Description, and Link Average Grade. "Link Source Types" requires the following inputs: Link Id, Source Type (vehicles types) and Source Type Hour Fraction (percentage of each type of vehicles in traffic).

The important factor in estimating the emissions is to simulate the change in vehicle operation due to delays. In MOVES, there are three options of simulating traffic activity:

I. Average Speed: Assigning an average speed to vehicles in a link or roadway. This method accounts for less inputs. However, it is less precise as compared to the other methods.
II. Link Drive Schedule: The drive cycle for each link is required. Second by second variation in vehicles speed needs to be entered. It is more precise than the Average Speed method.
III. Opmode Distribution: This requires more detailed inputs such as start, stop, idling hours, parked fraction, acceleration, deceleration of vehicles, etc. It is the best method to simulate the actual traffic.

The proximity of the estimated emissions to those of real life emissions depends on accuracy of the inputs. In this study, Average Speed method was considered due to its simplicity in characterizing the traffic on the roadway.

5.2. Calculating Inputs for MOVES from Work Zone user Cost method in LCCA.

The LCCA Work Zone user method is selected for generating inputs for MOVES 2014 for the following reasons:

- LCCA is a well-established method and it is being implemented by many state highway agencies for selecting alternate pavement designs. The software provided by FHWA to perform LCCA is based on FHWA's best practice methods [2].
- The LCCA has a well-defined methodology for estimating user costs due to delays; the same science can be used to generate the inputs for MOVES.
- LCCA and LCA are being integrated for analyzing the designs to address sustainability. Since both analyses need to make assumptions that may have significant influence, adapting the same methodology in both methods will reduce the number of assumptions.

The important factors for estimating user costs due to traffic delays are: projected AADT at the time of maintenance, hourly demand distributions, vehicle classification, work zone speed, vehicles speeds in case of queue formation, duration of lane closures, timing, work zone length, number and capacities of lanes during maintenance [9]. Similar inputs were required by MOVES for characterizing link and link source type, hence, the methodologies implemented in RealCost 2.5 LCCA software can be adapted for estimating emissions. The following steps demonstrate procedures for calculating the link length, speed and volume. The steps are in line with the work zone user costs estimates implemented in LCCA and explained by Walls and Smith [9]. The Design 1 and its first maintenance are explained in this methodology. One lane on each side is closed from 9AM—5PM, i.e., two lanes on both sides are open for traffic instead of three. Under normal conditions the highway speed is 60 miles per hour (MPH) whereas during maintenance it is reduced to 40 MPH over a 1 mile work zone distance.

Step 1: The future traffic is calculated using the following equation 1 [9]

$$\textit{Future Year AADT} = (\textit{Base Year AADT}) \times (\textit{Vehicle Class \%}) \times (1+\textit{growth rate})^{(\textit{Future yr} - \textit{Base yr})} \quad (1)$$

For the same traffic, the AADT in 2022 (8.3 years first maintenance from 2014) is expected to be 130,016.

Step 2: Hourly demand can be calculated using the following equation 2 [9]

$$\textit{Hourly Demand} = (\textit{AADT}) \times (\textit{Hourly Distribution Factor}) \times (\textit{Hourly Directional Factor}) \quad (2)$$

Step 3: Table 1 shows default hourly distributions for urban (columns a—d) from Micro BENCOST [9] which was used in this example. Using equations 1 and 2, the typical inbound and outbound traffic in 2022 is shown in column e and f of Table 1.

Step 4: It is important to assume the capacity of a highway under various conditions during maintenance. If the demand is less than the capacity, no queue will form allowing traffic to freely flow. Once a queue develops, all approaching vehicles must not only slow down before proceeding through the work zone itself, but they also must stop at the upstream end of the queue and creep through the length of the physical queue under forced flow conditions [9]. Typically, during maintenance there will be three capacities:

I. The free flow capacity of the highway under normal operating conditions is considered to be 2,180 vehicles per hour (VPH) per lane in this study(as per Tables 3.4 to 3.6 of Walls and Smith [9]).

II. Reduction in capacity of the highway when the work zone is in place is considered to be 1415 VPH per lane in this study (as per Figure 3.4 of Walls and Smith [9]).

III. The capacity of the highway to dissipate traffic from a standing queue is considered to be 1818 VPH per lane in this study, as per the recommendations of Greenroads Manual [14] and Walls and Smith [9].

Step 5: In this step, the simplified method proposed by Walls and Smith [9] was employed to calculate queue lengths. The method involves calculating the number of queued vehicles to the available lanes and multiplying the number of vehicles per lane by an assumed average vehicle length that includes the space between the vehicles. In this study, the distance between vehicles in the queue is assumed to be 30 feet in length.

Step 6: The speed of the vehicles in a queue can be determined by using a forced flow average speed versus a volume to capacity (v/c) ratio. Graphs for the level of service F are contained in the earlier editions of the highway capacity manual as described by Walls and Smith, [9]. When two lanes are open instead of three then the volume of highway will be 2,830 VPH (1,415X 2=2,830). The capacity of highway is 6,540 VPH (3 X 2,180)). The V/C ratio is 0.43 and the corresponding speed from Fig.1, is 8 MPH. Even though all the lanes are open after maintenance, the existing queue cannot reach the free flow capacity instantly. Queue dissipates gradually and the speed during the transition can be calculated as mentioned above where the volume will be three times the queue dissipation capacity (1,818 X 3=5,454). The V/C ratio is 0.83 and the corresponding speed from Fig.1, is 18 MPH.

Table 1. Default Hourly Distributions for Urban Area from Micro BENCOST

Hour (24-hr Clock) (a)	% ADT (b)	Inbound (c)	Outbound (d)	Inbound in 2022 (e)	Outbound in 2022 (f)
0-1	1.2	47	53	734	828
1-2	0.8	43	57	448	593
2-3	0.7	46	54	419	492
3-4	0.5	48	52	312	338
4-5	0.7	57	43	519	392
5-6	1.7	58	42	1283	929
6-7	5.1	63	37	4182	2456
7-8	7.8	59	41	5989	4162
8-9	6.3	59	41	4837	3362
9-10	5.2	55	45	3722	3045
10-11	4.7	46	54	2814	3303
11-12	5.3	49	51	3380	3518
12-13	5.6	50	50	3644	3644
13-14	5.7	50	50	3709	3709
14-15	5.9	49	51	3762	3916
15-16	6.5	46	54	3891	4568
16-17	7.9	45	55	4627	5655
17-18	8.3	45	55	4861	5941
18-19	5.9	46	54	3532	4146
19-20	3.9	48	52	2436	2639
20-21	3.3	47	53	2019	2276
21-22	2.8	47	53	1713	1931
22-23	2.3	48	52	1437	1557
23-24	1.7	45	55	996	1217

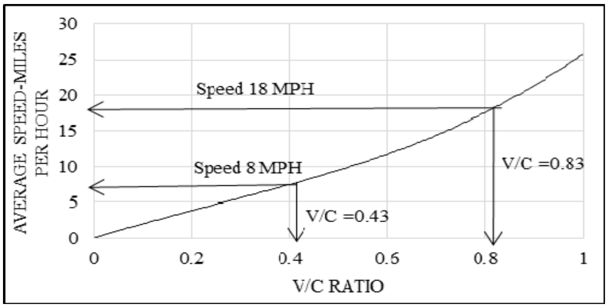

Fig. 1 . Average Speed versus V/C Ratio (Adapted from [9])

The

Table 2 shows the queue lengths estimation, queue speed, and VPH that cross the queue length. It is evident that once one lane on each side of the highway closes from 9AM—5PM, queue begins to form starting at 9AM and extends up to 9PM (shaded area in the table). For brevity, inbound calculations for hours 9 and 10 are discussed. The inbound traffic at 9AM is 4,837 vehicles and capacity is only 2,830 (2 X 1, 415), which leads to 2,007 queued vehicles. The inbound traffic at 10AM was 3,722 vehicles, however, 2,007 vehicles were already in queue, so the total demand increases to 5,729 (3,722 plus 2,007). The capacity is 2,830, so the total vehicles queued by the end of hour is around 2,899 (5,729-2,830). By the end of the 9AM hour, the queue length is 2,007 times 30 feet which is around 5.7 miles and work zone length is 1 mile. The total link length is 5.7 miles plus 1 mile which yields a total of 6.7 miles. The total number of vehicles in the total link 4,837. The average speed is considered as 8 MPH.

The impacts from traffic delays are measured as the difference between emissions with and without maintenance. Table 3 shows the summarized output for two pollutants (carbon dioxide (CO_2), and methane (CH_4)) in grams. The additional impact due to maintenance for the present scenario is 3,356 x 10^6 grams of CO_2, and 3.0 x 10^8 grams of CH_4 per day. The total impact due to maintenance depends on the total days of maintenance.

Table 2 Estimation of Queue length, Queue speed and Vehicles per hour

	Demand				Queue Rate		No of Vehicles Queued		Inbound				Outbound			
Time (a)	Inbound (b)	Outbound (c)	Lanes Open (d)	Capacity (e)	Inbound (f)	Outbound (g)	Inbound (h)	Outbound (i)	Queue Speed (j)	Queue length (k)	Inbound link length(j+k) (l)	Vehicles per hour (VPH) (m)	Queue Speed (n)	Queue length (o)	Outbound Link Length (n+o) (p)	Vehicles per hour (VPH) (q)
1	734	828	3	6540	-5806	-5712	0	0	60	0.00	1.00	734	60	0.00	1.00	828
2	448	593	3	6540	-6092	-5947	0	0	60	0.00	1.00	448	60	0.00	1.00	593
3	419	492	3	6540	-6121	-6048	0	0	60	0.00	1.00	419	60	0.00	1.00	492
4	312	338	3	6540	-6228	-6202	0	0	60	0.00	1.00	312	60	0.00	1.00	338
5	519	392	3	6540	-6021	-6148	0	0	60	0.00	1.00	519	60	0.00	1.00	392
6	1283	929	3	6540	-5257	-5611	0	0	60	0.00	1.00	1283	60	0.00	1.00	929
7	4182	2456	3	6540	-2358	-4084	0	0	60	0.00	1.00	4182	60	0.00	1.00	2456
8	5989	4162	3	6540	-551	-2378	0	0	60	0.00	1.00	5989	60	0.00	1.00	4162
9	4837	3362	2	2830	2007	532	2007	532	8	5.70	6.70	4837	8	1.01	2.01	2684
10	3722	3045	2	2830	892	215	2900	747	8	8.24	9.24	5730	8	1.41	2.41	3683
11	2814	3303	2	2830	-16	473	2883	1220	8	8.19	9.19	5713	8	2.31	3.31	4742
12	3380	3518	2	2830	550	688	3433	1908	8	9.75	10.75	6263	8	3.61	4.61	8345
13	3644	3644	2	2830	814	814	4247	2722	8	12.07	13.07	7077	8	5.16	6.16	12571
14	3709	3709	2	2830	879	879	5126	3601	8	14.56	15.56	7956	8	6.82	7.82	11850
15	3762	3916	2	2830	932	1086	6059	4687	8	17.21	18.21	8889	8	8.88	9.88	12149
16	3891	4568	2	2830	1061	1738	7120	6425	8	20.23	21.23	9950	8	12.17	13.17	13726
17	4627	5655	2	2830	1797	2825	8917	9250	8	25.33	26.33	11747	8	17.52	18.52	15952
18	4861	5941	3	5454	-593	487	8324	9737	18	15.76	16.76	13778	18	18.44	19.44	15191
19	3532	4146	3	5454	-1922	-1308	6402	8429	18	12.12	13.12	11856	18	15.96	16.96	13883
20	2436	2639	3	5454	-3018	-2815	3384	5615	18	6.41	7.41	8838	18	10.63	11.63	11069
21	2019	2276	3	6540	-4521	-4264	0	1351	60	0.00	1.00	2019	18	2.56	3.56	6805
22	1713	1931	3	6540	-4827	-4609	0	0	60	0.00	1.00	1713	60	0.00	1.00	1931
23	1437	1557	3	6540	-5103	-4983	0	0	60	0.00	1.00	1437	60	0.00	1.00	1557
24	996	1217	3	6540	-5544	-5323	0	0	60	0.00	1.00	996	60	0.00	1.00	1217

Table 3 Output Emissions from MOVES 2014 for Design 1 First Maintenance

HOUR	Carbon dioxide (grams)			Methane (grams)		
	Maintenance (9am-5pm) (a)	No Maintenance (b)	Additional impact (a-b)	Maintenance (9am-5pm) (e)	No Maintenance(f)	Additional impact (e-f)
1	1192663	1192663	0	7	7	0
2	790123	790123	0	5	5	0
3	687210	687210	0	4	4	0
4	487895	487895	0	3	3	0
5	680013	680013	0	4	4	0
6	1642540	1642540	0	10	10	0
7	4914832	4914832	0	30	30	0
8	7615924	7615924	0	46	46	0
9	51644808	6265579	45379229	576	37	539
10	85501138	5263809	80237329	931	31	900
11	99259850	4808629	94451221	1065	28	1037
12	163729536	5476490	158253046	1734	28	1706
13	260169444	5833932	254335512	2726	34	2692
14	306428904	5976728	300452176	3183	35	3148
15	331441492	6204627	325236865	3430	36	3394
16	373447640	6841076	366606564	3860	39	3821
17	436090664	8305324	427785340	4515	48	4467
18	638899312	8697225	630202087	4887	51	4836
19	490603080	6136956	484466124	3780	35	3745
20	192417632	4014748	188402884	1872	23	1849
21	3368249	3368249	0	19	19	0
22	2840501	2840501	0	17	17	0
23	2322135	2322135	0	8	8	0
24	1709177	1709177	0	10	10	0
Cumulative			3355808377			32134

6. Influence of Maintenance Timing on Emissions

The timing of maintenance effects the traffic delay emissions. To reveal the importance of timing of maintenance, the GWP for various pavement maintenance strategies was estimated for four different scenarios (column b of Table 4). The time period from 9AM —5PM was considered to reflect maintenance during peak hours. 10PM — 6AM was considered to reflect maintenance during nights. The time period from 11AM —3PM and 8PM — 12AM was considered to reflect maintenance during non-peak hours. The GWP estimated for various scenarios are summarized in Fig.2, and Table 4. It is evident that traffic delay emissions will be dominating factor if maintenance happens during peak hours (scenario 2 and 3) and overshadows other phases of LCA, and vice versa during non-peak hours (scenario 3). Further analysis reveals that when emissions due to delays are not considered in LCA the prominent environmental impact is due to material extraction. The GWP is around 65-75 % due to material extraction, if traffic delays are ignored in analysis. If maintenance during peak hours of traffic is considered in LCA then GWP due to material extraction phase shifted to 5-10% from 65-75% percentages. These differences demonstrate the significance of traffic delays emissions in LCA of pavements.

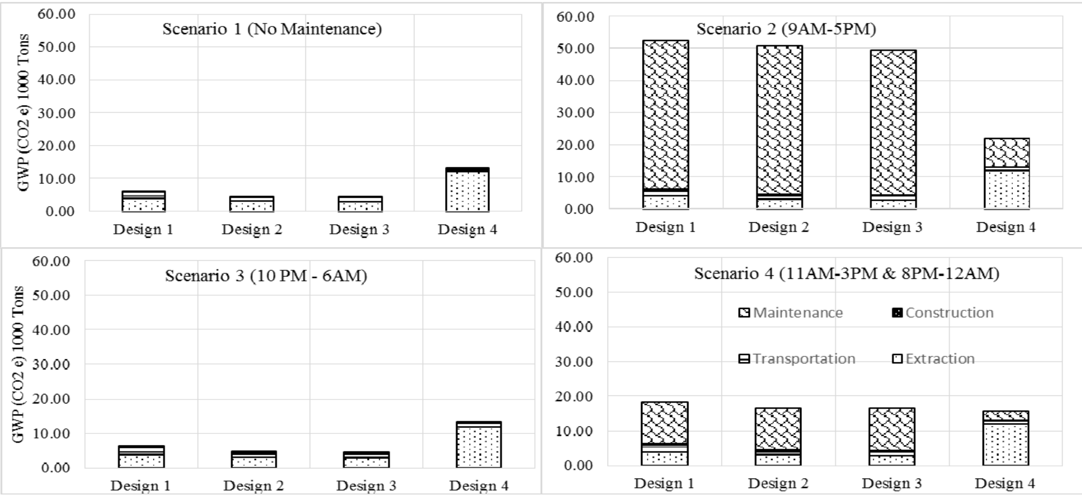

Fig. 2 .GWP of Alternative Designs for Different Maintenance Scenarios.

Table 4 Influence of Maintenance Timing on GWP

SNO (a)	Scenario (b)	Highest GWP per mile (1000 tons CO_2e)			Lowest GWP per mile (1000 tons CO_2e)			Difference in GWP (Highest vs Lowest) (i)
		Design (c)	GWP (d)	Dominating Phase (e)	Design (f)	GWP (g)	Dominating Phase (h)	
1	No traffic delay emissions	4	13.03	Material Extraction (66%)	3	4.3	Material Extraction (66%)	8.73
2	Lanes closed from 9AM—5PM	1	52.45	Traffic Delay Emission (88%)	4	21.81	Material Extraction (55%)	30.64
3	Lanes closed from 10PM—6AM	4	13.03	Material Extraction (66%)	3	4.33	Material Extraction (66%)	8.7
4	Lanes closed from 11AM—3PM and 8PM—12 AM	1	18.39	Traffic Delay Emission (67%)	4	15.77	Material Extraction (76%)	2.62

7. Conclusions and Recommendations

The proposed methodology can be implemented to estimate traffic delay emissions by agencies during their selection of pavement designs. Since state highway agencies are familiar with LCCA methodology, the required inputs for MOVES can be easily obtained. Additionally, MOVES 2014 is a reliable simulation tool, which is regularly updated and is available at no cost.

Emissions during traffic delays can surmount the emissions due to other phases and the needs to be considered during the design and planning phases of a project. Although maintenance related emissions can significantly influence carbon footprint, the assumptions made in the LCA analysis should be followed. For instance, if design 3 was selected for construction and assumed that the maintenance will be performed during night hours, then the actual maintenance should be executed during night hours otherwise the benefit of selecting design 3 will be compromised. All possible scenarios should be evaluated and scenarios should be corresponding to the actual maintenance operations.

This study assumed that traffic cannot be re-routed and has to bypass the work zone. Further research for estimating AADT considering traffic diversion is required. Vehicles were assumed to travel at a uniform speed in the queues but, in reality vehicles are subjected to numerous modes such as stop, start, accelerate, decelerate etc. Future research in developing models to simulate future traffic movements during maintenance considering the various modes are required.

The authors of this study are aware that the proposed methodology yielded simple estimates of possible future emissions and that the actual emissions will differ. In accordance with Santero and Horvath [6], the uncertainties prevail in estimates, but it may still be beneficial to understand the scope of potential impacts for each life cycle components. Estimate the benefits and drawbacks of various maintenance schedules before performing LCA.

The LCA comprises of many environmental and social factors and the selection of pavement design may change than what was observed in this study. Although various regular maintenance do occur on selected design types or premature failure occurs, it was not considered due to lack of data available.

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